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Study of the physical parameters of pulsating stars by semi-empirical photometric methods

THESES

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1. Background and scientific goals

The low-mass pulsators of the horizontal branch – the variables of the RR Lyrae type – play a very significant role in many fields of astrophysics. Their pulsations can be successfully modelled, which does not only make them essential test objects for pulsation theory, but also gives us the opportunity to put substantial theoretical constraints on their global physical parameters. Due to the information we can gather on these basic quantities, these stars provide important tools for the study of our cosmic environment and for the understanding of certain aspects of stellar evolution. Thanks to their relatively high luminosity and the large amplitude of their light variation, they are suitable for the analysis of the structure, formation, and evolution of the population II sub-systems of our Galaxy, as well as those of the extragalactic objects within the Local Group. Based on the linear correlation between their periods and absolute brightnesses, they can be used as accurate distance indicators, therefore they provide an important step of the cosmic distance scale. The close relationship between their light curves and fundamental parameters manifests itself in various empirical relations. Based on such relations, among others, they can also be employed as tracers of the chemical composition and chemical evolution of their host systems. RR Lyrae stars pulsating simultaneously in two radial modes play a particularly important role in the study of physical parameters because their precisely measureable periods pose significant constraints on the stellar structure. In my thesis I address the problem of deriving accurate physical parameters of stars based on multi-color time-series photometric data, and models of stellar atmospheres, evolution, and linear pulsation. Concentrating mainly on variables of the RR Lyrae type, I employ diverse methods with both empirical and theoretical approach in order to put tight constraints on their fundamental parameters and those of their host systems, and to probe various interrelations between them.

In the possession of the extensive multi-color database of the double-mode RR Lyrae star BS Comae, there arose the question of how an accurate estimate could be made for the fundamental parameters of the star based on these available photometric data, taking consistently into account the constraints of stellar pulsation and evolution. This problem lead to the development of a new method for stellar parameter determination. Based on the results of this method the complete double-mode parameter space could be studied, giving an insight into the various relations between the stellar parameters.

In line with the aforementioned investigations, I started a two-year (2007 – 2008) observational program for the time-series photometric survey of the globular cluster M53, whose time-domain properties were relatively poorly studied beforehand. My goal was to acquire precise time-series data of its known pulsating stars, detect new variables, and determine the basic physical properties of the cluster based on the photometric data.

2. Methods

The basis of most scientific results discussed in my thesis is formed by CCD time-series photometric data. The acquisition of these data needed a careful planning and execution of a series of observations. I participated in the monitoring of the light variations of BS Comae as the team member of the Konkoly Blazhko Survey, while I carried out the time-series photometric survey of M53 as an own, independent observational project. The first step in the processing of the observational material is the basic reduction of the images, for which I employed the standard calibration methods of astronomical image processing. Depending on the characteristics of the observed target, this is followed by subsequent transformations of the images, then the measurement of the flux variations of the point sources throughout the frame by some photometric procedure, and a post-processing of the time-series afterwards. For these tasks, among the standard methods, I also applied a combination of new reduction techniques. In these further steps of reduction I employed aperture and PSF profile-fitting photometry, the method of optimal image subtraction, and the trend filtering algorithm (TFA).

For the quantitative study of the light curves, the mathematical analysis of the photometric time-series is required. In my research I investigated periodic light variations of pulsating stars, employing the inventory of standard Fourier analysis. This means, on the one part, the identification of frequency components of the pulsation with the aid of some time–frequency transformations, and, subsequently, the determination of the optimum mathematical model of the time variations by an iterative prewhitening procedure, performing linear and nonlinear fitting to the data in each step. For evaluating the results and for the error analysis, various statistical methods and simulations are needed as well.

For the determination of the physical parameters of the studied objects I applied diverse empirical relations and theoretical models. As for these latter I used a linear pulsation code, and the numerical results of stellar evolution calculations and models of stellar atmospheres. I determined the global parameters of the studied stars by various combinations of these model results, which means, from a mathematical point of view, the algorithmic implementations of complex multi-dimensional fitting problems.

Besides the software implementation of the new methods, the common demand for the solution of special data processing tasks and other practical problems also required the writing of new computer programs and scripts, as well as the modification of existing codes. Thus, a continuous software development and testing formed an integral part of my PhD research.

3. Theses

3.1 Analysis of double-mode RR Lyrae stars

I. As a team member of the Konkoly Blazhko Survey, I participated in the two-year (2005 – 2006) photometric observational program of the double-mode field RR Lyrae star BS Comae. Due to the large number of data points and the high phase coverage of the light variation, the time series acquired by these observations form the most extensive multi-color photometric database of this type of variable to date. I performed the data reduction and carried out subsequent observations for the absolute calibration of the light curves. Based on the detailed analysis of the time-series, the light variation of the star can be fully described with 15 frequencies of the two pulsation modes and their linear combinations within the observational accuracy, and the presence of non-radial modes can be excluded above the ~ 2 mmag level. In addition I analyzed the regularities in the amplitudes and phases of the pulsation components [1].

II. I developed a new method for determining the fundamental physical parameters of double-mode RR Lyrae stars (CPE method). The method allows one to strongly confine all basic stellar parameters of an object solely from its observed periods, by taking into account the combined theoretical constraints of linear pulsation models and horizontal branch stellar evolution models. The periods of an object determine a sequence of solutions for its mass, luminosity, effective temperature, and metallicity, with the time elapsed from the zero age horizontal branch being a free parameter within the linear excitation domain of the modes. In possession of additional observational data, one is able to further constrain the time parameter, increasing the precision of all other parameters at the same time. For this aim, even precisely calibrated average color indices can be sufficient [2,3].

III. With the aid of the CPE method I studied the fundamental physical parameters of BS Comae. Based on the available precisely calibrated multi-color photometric data I made an independent estimate on the effective temperature and metallicity of the star, using stellar atmosphere models. The results were consistent with those obtained by the CPE method. By constraining the CPE solution sequences with the independent photometric information I determined the mass and the luminosity of the star with an accuracy of $\sim 1\%$. I investigated the sensitivity of the results against different model constructions. I showed that the derived physical parameters are only weakly sensitive to the period shifts predicted by current non-linear convective hydrodynamical models. Furthermore, the differences introduced by convection and non-linearity are systematic, and therefore they can be easily predicted [2].

IV. The CPE method enabled a homogeneous study of several additional double-mode

RR Lyrae stars. I determined the physical parameters of altogether 20 more stars from the Galactic Field and the Large Magellanic Cloud. The stars were selected to cover wide ranges of periods and period ratios, implying diverse stellar parameters, uniformly covering most of the stellar parameter space populated by double-mode RR Lyrae stars. The derived metallicity and color index values show a general consistency with observational data. The results provided an insight into the the intrinsic properties of the double-mode parameter space. The derived sets of solutions yielded various important theoretical relations between stellar mass, luminosity, and metallicity. In the case of some parameter combinations, the relations are degenerate in time, i.e., they are nearly independent of evolutionary effects. Based on the CPE method, I got very tight simple linear relations on the logarithmic scale between the period of the fundamental mode and the average values of the stellar radius and density, and the gravitational acceleration. Based on the comparison of the theoretical $\log P$ – Wesenheit-index (PLC) relation with the fully empirical one (Kovács & Walker 2001, A&A, 371, 579), I showed that the cosmic distance scale stemmed from the results of the CPE method is compatible with the generally accepted one. I pointed out that the slight slope difference between the above relations can be caused by their soft metallicity dependence. I also demonstrated that the exact form of the various relations obtained in this study are only marginally dependent on the effects of convection and non-linearity [2].

3.2 Time-series photometric survey of the globular cluster M53

V. Covering two adjacent seasons in 2007 and 2008, I carried out a comprehensive time-series photometric survey of the globular cluster M53, with the goal of completing the census of its variable stars, and analyzing their basic physical properties. I performed the reduction of the observational material with the subsequent application of the optimal image subtraction method (Alard 2000, A&AS, 144, 363) and the trend filtering algorithm (TFA, Kovács 2005, MNRAS, 356, 557), utilizing information held by the time series of many other detected point sources for filtering out various systematics from the data in the post-processing phase. I employed this method for the first time on both globular cluster data and for time-series with a low number (a few hundred) of data points. The reduction technique has proven to be very effective, and its further application in the photometric study of additional globular clusters and galaxies is well established. In addition to the improvement of the precision of the light curves, the application of the above methods considerably increased the detection probability of weak signals, which led to the discovery of many new variable stars in the cluster. I found altogether 12 new variables (2 RR Lyrae stars, 7 short periodic stars, and 3 long-period variables), and detected a hitherto unknown modulation in the light curves of 3 RR Lyrae stars.

VI. Since there were ample amounts of single-mode RR Lyrae stars in M53 with calibrated V and I light curves, it was possible to determine the distance of the cluster based on the empirical PLC relation. I demonstrated for the first time on an empirical basis that first overtone RR Lyrae stars, after a proper period shift, follow the same linear $\log P_0 - W(V-I)$ relation as the fundamental mode ones. By using the earlier Baade–Wesselink calibration of this relation (Kovács 2003, MNRAS, 342, L58), I derived the precise dereddened distance modulus of $16,31 \pm 0,04$ mag for the cluster [4].

VII. Based on the available multi-color photometric data, and models of stellar atmospheres and evolution I made an accurate estimate on the metallicity of the red giant stars in the cluster. The estimated value of $-2,12 \pm 0,05$ dex is in a fine agreement with the results of earlier spectroscopic studies, and shows a remarkable, $\sim 0,5$ dex difference compared to the iron abundance calculated from the empirical relation between the [Fe/H] index and the Fourier parameters of RR Lyrae stars (Jurcsik & Kovács 1996, A&A, 312, 111). This discrepancy, previously noted also in the case of some other low-metallicity globular clusters, cannot be explained with the effect of the enhanced alpha-element abundance generally found in these objects. I suspect that the reason of this discrepancy most probably lies in the lack of sufficient low-metallicity stars in the calibration sample of the widely used Fourier-method, although precise spectroscopic abundance measurements would be required for a more secure assessment of this problem [4].

4. Summary

I devised a new method for the physical parameter determination of double-mode RR Lyrae stars. With this method one is capable to very accurately derive the fundamental parameters of an object, relying on horizontal branch evolution models, linear pulsation models with low computational demand, and performing simple general corrections on the results. By the application of this method on a representative sample of objects I found important theoretical interrelations between the basic stellar parameters. I carried out a two-color photometric survey of M53 in order to study the time-domain properties of its variable stars. With the aid of novel reduction techniques I discovered new variables in the cluster and significantly extended the photometric data base of its RR Lyrae stars. Relying on the data of these latter objects I determined the precise dereddened distance of M53. I gave an accurate estimate on the average metal content of the cluster based on theoretical models and multi-color photometric data of red giant stars. I pointed out the current problems of using RR Lyrae stars as metallicity indicators. The new methods described and employed in my thesis can be very widely used, therefore they can contribute to the better understanding of RR Lyrae stars as well as to the more effective utilization of these objects in the study of distant stellar populations.

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